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Calibration of HDM-4 emission models for Indian conditions

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Abstract

The Highway Development and Management-4 (HDM-4) tool has been widely used for the pavement management activities across the world. This tool has inbuilt pavement performance prediction models, vehicular performance models and economic analysis tools. Exhaust emissions are one of the important outputs of vehicular performance models that are helpful in assessing viability of investment options and environment impact assessment activities. There are seven exhaust emission models (for different components like hydro carbon, carbon monoxide, particulate emissions etc.) available within HDM-4. These models are required to be calibrated so that the predictions made by calibrated HDM-4 models represent the specific local ground conditions. The work presented here is an attempt to calibrate the HDM-4 emission models to Indian conditions. Initially sensitivity analysis of emission models was conducted to find sensitive input variables in emission model that affect model output significantly. It was found that operating weight, pavement gradient and vehicle life are very sensitive inputs into HDM-4 emission models. Based on the sensitivity analysis and data obtained from a previous study were used in calibration of emission models for Indian conditions. Further these calibrated emission models were used to predict emissions for urban conditions prevailing in India. Comparison of predicted and measured values indicate that all emission models for two lane road and Carbon Monoxide emission model for four lane road over-predicts for two wheelers, car, light commercial vehicles and busses, while under-predicting for trucks.

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Keywords: Highway Development and Management; Calibration; Sensitivity analysis; Emission models

1. Introduction

The Highway Development and Management (HDM-4) model, originally developed by World Bank is widely used as a planning and programming tool for the highway expenditure and maintenance activities throughout the world. HDM-4 is a computer model that simulates physical and economic conditions over the period of analysis

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for the series of alternatives and scenarios specified by the user. It mainly consists of Road Deterioration & Works Effects (RDWE) models and Road User Effects (RUE) models. The RDWE models consist of pavement distress models whereas RUE models consists of vehicle operation, travel time, accidents and emission effects models. There are seven components of the exhaust emissions are modeled in the HDM-4. They are Hydrocarbon (HC), Carbon Monoxide (CO), Nitrogen Oxide (NO_x), Sulphur Dioxide (SO₂), Carbon Dioxide (CO₂), Particulates (PAR) and Lead (Pb). All the seven emission models predict the vehicle exhaust emission as function of road, traffic and vehicle characteristics. The primary characteristics used for the modeling of the vehicle emission are traffic volume and its composition, type and geometry of the road section, vehicle operating speed, fuel type and vehicle life (HDM-4 manual, Volume 4 and 7, 2000).

The HDM-4 emission models have been developed as a result of the field experiments conducted in wide range of conditions having different technology, climate and economic environments. During the development of HDM-4 tool, only some input parameters were considered in model building while ignoring some input parameters. Some of the reasons for ignoring some input parameters are (i) incorporating all parameters would have made model too complex to handle, (ii) effect of each parameter on output couldn't be determined within the ranges observed, and (iii) collection of data regarding all parameters for all field conditions would be expensive (in terms of cost, time, effort) (HDM-5 manual, Volume 5, 2000). Several calibration factors have been inbuilt within these HDM-4 emission models to account for these unaccounted local issues. These calibration factors can be adjusted to match the data/conditions that are collected/ existing locally.

With the calibrated HDM-4 emission models, it is possible to analyze the changes in the vehicular emissions as a result of implementing different road maintenance and improvement options, or when there are major changes to the fleet using the road network (for example, due to improved vehicle technology). Such a calibrated HDM-4 emission model will help in making choices regarding pavement maintenance activity for Indian conditions. Such an attempt to calibrate emission models (within HDM-4 framework) is reported in here. The primary purpose of this article is to find most sensitive parameters in HDM-4 emission models, and calibrate the same for Indian conditions. Within HDM-4 framework, calibration of only HC, CO, NO_x and PAR emission models has been conducted in this study.

2. Study Area and Data Collection

The data for the calibration of the HDM-4 emission models was extracted from the report published on the emissions in Delhi city by National Environmental Engineering Research Institute (NEERI, 2008). The locations selected for the calibration and validation of the emission models are Dhaula Kuan and Ashram Chowk study zone, respectively. As per this study, emissions at these locations are predominantly by motorized traffic. At micro-level, 2km x 2km monitoring sites were setup at these locations and emission load was calculated for various types of roads and vehicle class.

Arterial roads, main roads and feeder roads were identified in these study zones. The number of lanes in arterial roads, main roads and feeder roads were 4, 2, and 1 respectively. The average length of road in study area along arterial roads, main roads and feeder roads was 5.4 km, 1.4 km and 8.5 km, respectively. Based on the vehicular data collected in the study zone, composition of the traffic has been calculated under six broad categories namely, Two Wheelers (2W), Three Wheelers (3W), Four Wheelers (4W, like car, jeep, van, and taxi), Light Commercial Vehicles (LCV, like mini trucks, mini buses), Trucks and Buses. The AADT and its composition in the study zones are given in Table 1.

The data regarding age-wise percentage composition of the fleet was extracted from Regional Traffic Office (RTO) records. The age-wise composition of the vehicles is given in Figure 1.

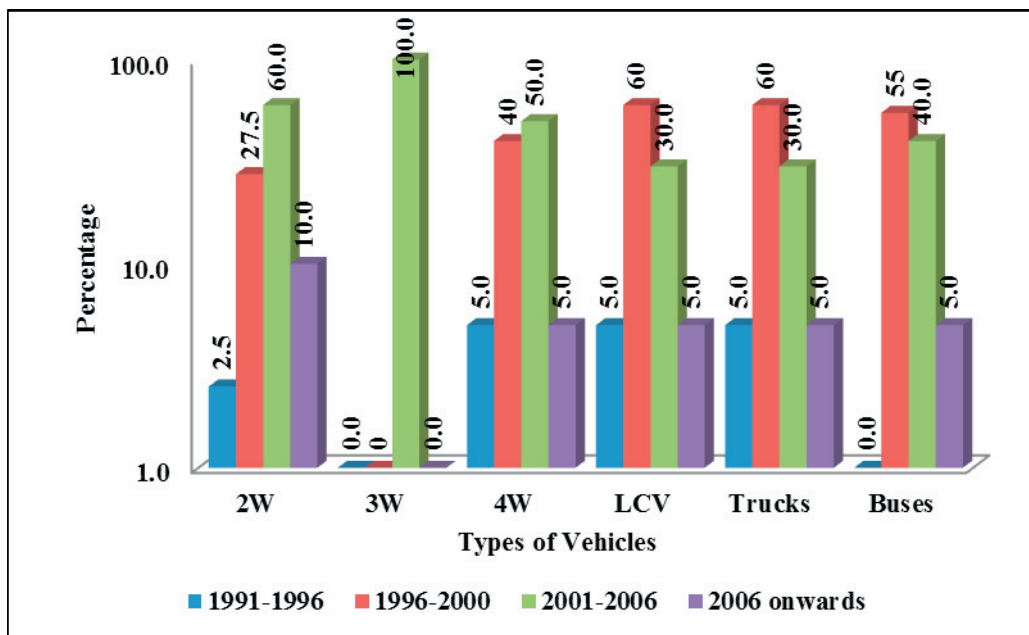
To evaluate the annual emission load at these sites, Vehicle Air Pollution Information System-1.01 (VAPIS 1.01) tool was selected. The emission load is a product of (i) number of vehicles in i^{th} class (N_i), (ii) kilometers of travelled by i^{th} vehicle class in a given year (V_{KTI}), and (iii) emission factor for i^{th} vehicle class (EF_i). Emission

factor is dependent on type of fuel, load, life of vehicle etc. Emission factors for different types and makes of the vehicles were obtained from report by Automotive Research Association of India (ARAI 2008), Pune.

Table 1: Details of traffic count survey

Study Zone	AADT	AADT Composition (%)					
		TW	3W	4W	LCV	Trucks	Buses
Dhaura Kuan, Arterial Roads	123906	29.6	8.3	50.7	4.2	3.6	3.6
Ashram Chowk, Arterial Roads	124225	31.8	10.3	46.8	3.9	3.9	3.4
Dhaura Kuan, Main Roads	40728	31.4	8.6	46.3	7.2	4.0	2.5
Ashram Chowk, Main Roads	40923	33.7	10.6	42.7	6.6	2.7	3.7
Dhaura Kuan, Feeder Roads	11981	29.9	2.2	61.6	4.3	1.4	0.6
Ashram Chowk, Feeder Roads	10005	39.1	10.7	45.6	2.8	1.0	0.7

Figure 1. Fleet age composition



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3. Calibration Methodology

Calibration of HDM-4 emission models consisted of three stages namely, (i) sensitivity analysis, (ii) calibration of models and (iii) validation. In the sensitivity analysis stage, input variables that affect emission model output significantly were identified. In the second stage, HDM-4 emission models were calibrated to local conditions using the field data available. In the third stage emission values predicted by calibrated emission models were compared with additional data to check the accuracy. Flowchart of the calibration process is presented in Figure 2.

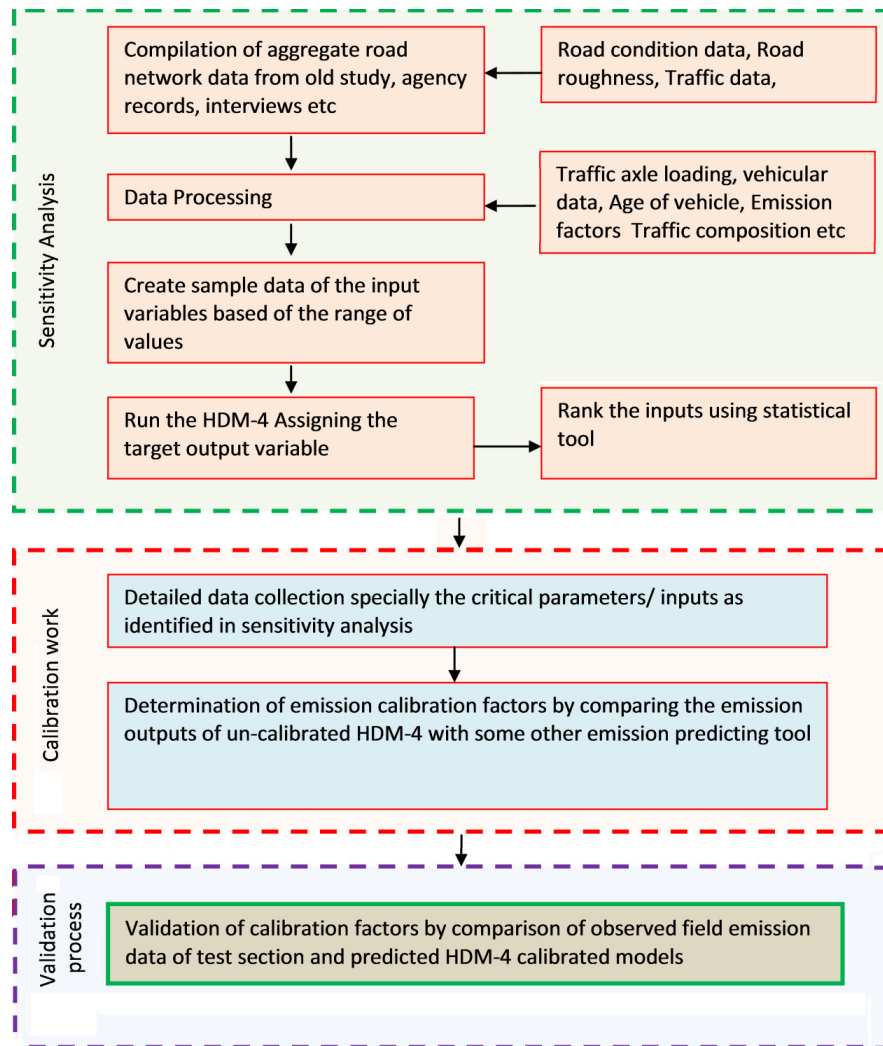


Figure 2: Flowchart for HDM-4 emission model calibration

3.1. Sensitivity Analysis

In the sensitivity analysis part, 35 variables were identified on which the vehicular exhaust emission depends (HDM-4 Manual, Volume-4). Among these 35 variables, 16 were from engine side, 4 were vehicle physical inputs and rest were on road geometric and traffic characteristics. Due to difficulty in accessing the engine parameters, these inputs were dropped from the sensitivity analysis. 100 simulations are run to generate the random Latin Hypercube Samples (LHS) for the ranges of the remaining 13 inputs (4 vehicle physical inputs + 9 geometric and traffic inputs). This resulted in generation of a rectangular grid of 100×13 sample points, each row being acting as a single data set. HDM-4 was run for these 100 data sets and the emission results were obtained. Spearman's rank correlation coefficient method was used for the ranking of the inputs. To identify the sensitive inputs in emission models, Spearman's rank correlation coefficients were plotted as tornado plots. The tornado plots for HC, CO, NO_x, and particulate emission models are presented in Figure 3a through 3d, respectively.

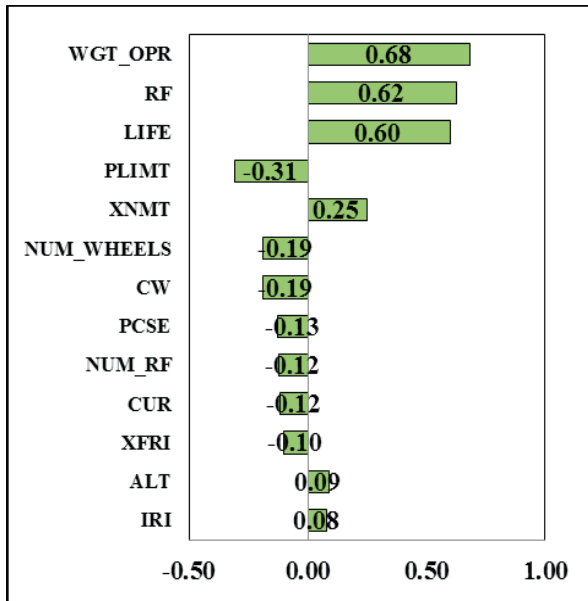
The most significant input is one whose Spearman correlation coefficient value is close to 1.0 or -1.0. The least significant input is one whose Spearman correlation coefficient value is close to zero. Positive sign shows the direct effect of the input over the output while -ve sign indicates the inverse effect of an input over the output. From the sensitivity analysis, an overall judgment can be made that vehicle life (LIFE) is the important input for all types of exhaust emission followed by operating weight (WGT_OPER). Engine performance deteriorates with the age of the vehicle and emissions are bound to increase as the age of the vehicle increases. The operating weight is again related to the fuel consumption and as the operating weight increases, the fuel consumption also increases and subsequently the emissions also increase.

3.2. Calibration of emission models

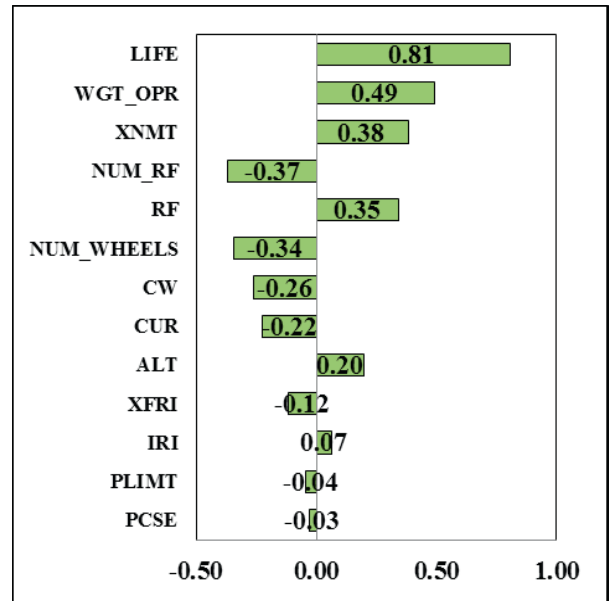
In all the HDM-4 emission models, there are two calibration factors, K_0 and K_1 . K_0 may be interpreted as a rotational calibration factor for a given exhaust emission whereas K_1 is a multiplicative factor for the Instantaneous Fuel Consumption (IFC) which is an explanatory variable (Islam et al. 2003). Calibration of both requires data identifying the influence of IFC, vehicle life (LIFE) and operating speed (SPEED) on the emissions. As such detailed data is not available, K_1 is left at its default value of 1.00 and calibration is carried out for K_0 only.

The output of the emission load obtained from the un-calibrated HDM-4 model was compared with output generated by VAPIS1.01 to calibrate the emission models. The calibration factors for various types of vehicle on the three road types of the study zone are summarized in Table 2.

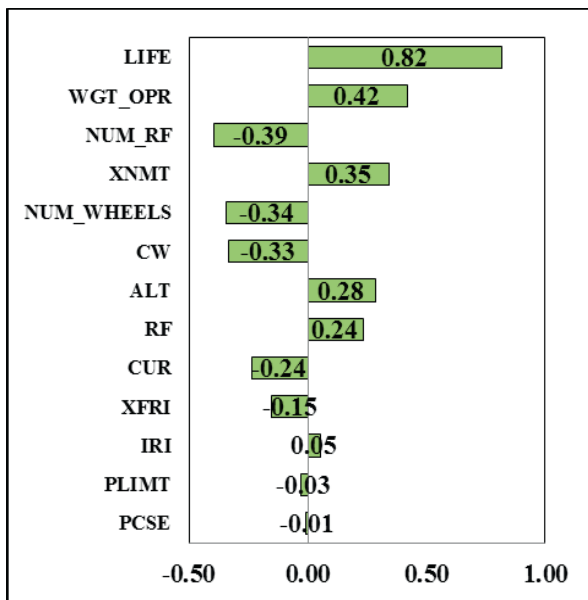
From the Table 2 it is clear that HDM-4 is over-predicting the HC emission for all vehicle classes except buses on all types of road classes. It is under-predicting the HC emission for buses by 1.06, 1.51 and 2.47 times for arterial road, main road and feeder roads respectively. It is over-predicting the hydrocarbon emission loads for 2W and 4W on all three types of roads. HDM-4 is over-predicting the carbon-monoxide emission load for 2W, 4W and LCV while under-predicting in case of Trucks on all road classes. For Buses, it is over-predicting for the arterial road and under-predicting for the main and feeder roads. This may be due to the varying speed of the buses on these roads. HDM-4 is under-predicting the NO_x emission for 2W for all the road classes and for buses on the main and arterial roads. For other vehicle classes it is over-predicting the NO_x emission ranging from 18.65% to 94%. HDM-4 is under-predicting the particulates emissions for the trucks in all the road types under study. The particulates emission for the LCV is highly under-predicted on all the road types so that the calibration factors so obtained is even outside the upper limit of 20 as per HDM-4 guidelines. This means the model coefficients are required to readjust for the local conditions or the HDM-4 modeling for the particulates is required to be re-evaluated. For validation purpose, the upper limit of 20 is fixed for LCV.



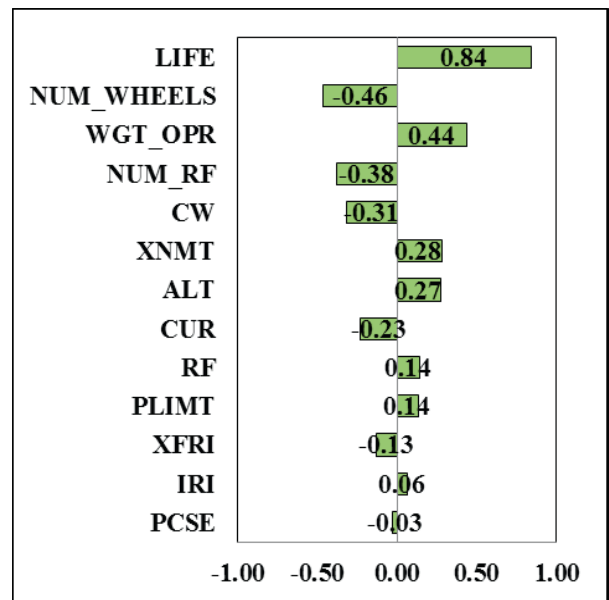
(a) HC Emission



(b) CO Emission



(c) NOx Emission



(d) Par Emission

Figure 3: Tornado plot for sensitivity analysis

Table 2: Calibration factors for Dhaula Kuan study zone

	Traffic type	Composition of traffic (%)	Calibration factor			
			HC	CO	NOx	PAR
Arterial Road	2W	29.6	0.14	0.11	4.07	1.01
	4W	50.7	0.15	0.13	1.03	0.76
	LCV	4.2	0.57	0.21	0.74	46.37
	Truck	3.6	0.72	2.33	0.82	2.2
	Bus	3.6	1.06	0.84	0.84	0.68
Main Road	2W	31.4	0.14	0.11	4.13	0.87
	4W	46.3	0.18	0.14	0.71	0.96
	LCV	7.2	0.41	0.14	0.5	37.34
	Truck	4	0.64	2.49	0.82	2.7
	Bus	2.5	1.51	1.23	1.26	1.25
Feeder Road	2W	29.9	0.07	0.07	1.5	0.78
	4W	61.5	0.07	0.06	0.81	0.2
	LCV	4.3	0.94	0.32	0.52	43
	Truck	1.4	0.71	3.57	0.86	2.84
	Bus	0.6	2.47	2.66	1.77	1.89

3.3. Validation of calibration results

The validation of the calibration results was done by applying the calibration factors obtained in previous step for each class of emissions to HDM-4 models for Ashram Chowk study zone data. The aggregated output (for all vehicle classes and for all road classes) obtained is then compared with the actual ground observations recorded at Ashram Chowk. Before comparing these two results, the predicted calibrated tail pipe emission as obtained by HDM-4 is first converted to ambient emission.

In order to meet the congestion effects on the emission models, the average annual AADT data of the Ashram Chowk was divided into five hourly time zones for the year. This distribution fairly accounted for the different levels of traffic congestion at different hours of the day, and on different days of the week and year. By defining the distribution of hourly flows over the 8760 (365 days x 24 hours) hours of the year, the AADT data at Ashram Chowk can be converted to hourly flow levels.

The observed and calibrated HDM-4 emission prediction results are presented in Figure 4. From Figure 4, it can be concluded that HDM-4 calibrated emission models are over-predicting the CO, HC and NOx emissions while under-predicting the PAR emission. The percentage variability of the emission is from 21.39 % to 33.87%. The reasons for the variability in the results may be due to short sampling of the observed data (collected for 21 days, 7 days in each season of winter, post monsoon and pre-monsoon). The variability may also arise as it is very difficult to collect the data for a confined area of 2km x 2km presuming that concentrations at all the locations are same. Moreover the ambient concentration as detected by the receptor depends on many factors such as wind strength and direction, climatic conditions etc. The over-prediction of PAR may be due to the fact that HDM-4 is giving the PAR of the tail pipe emission only but the ground observation also includes the paved road dust due to movement of traffic.

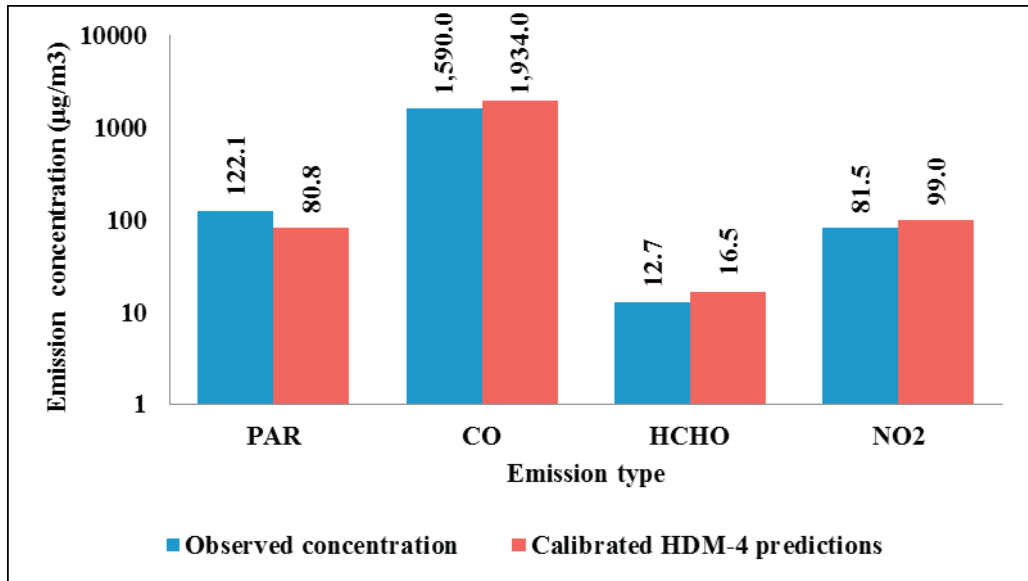


Figure 4. Observed and calibrated HDM-4 emission predictions, Ashram Chowk

4. Conclusions

The sensitivity analysis of the emission models shows that vehicle life is the most sensitive input followed by operating weight for CO and NO_x emission models. For HC emission model, operating weight is the most important input followed by RF. For particulates, vehicle life is the critical input followed by number of wheels and operating weight.

The validation of emission models shows the variability range of observed and calibrated predicted emissions types under study is from 21.39% to 33.87%. This variability can be attributed to limited data availability. However, the current validation may be treated as satisfactory and emission calibration factors evaluated can be adopted for the emission predictions for the urban traffic conditions prevailing in India using HDM-4.

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